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CONTRIBUTION OF SUSPENDED PARTICLES TO FLUID MIXING IN RECIPRO-MIXING WITH A DISK IMPELLER

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Abstract. Measurements of power and mixing time were conducted in particle suspensions by using a mixing system with a disk impeller reciprocated up and down in a cylindrical vessel. In a dilute suspension of particle volume fraction, ϕ, less than 0.2, the power number was almost the same as that in mixing homogeneous liquids but the time required for fluid mixing was decreased with increasing ϕ. In the suspension of ϕ equal to 0.01, the mixing time was well correlated with the gravitational settling velocity of the suspended particles. In a dense suspension of ϕ larger than 0.3, the power number increased appreciably and longer time was required for fluid mixing. From the variations of mixing time with the power input per suspension volume, it has been confirmed that the energy required for fluid mixing in a dilute suspension of ϕ less than 0.2 is smaller than that for mixing without particles. This suggests that the gravitational potential energy can be utilized for enhancing fluid mixing by the particle motion relative to the fluid motion.

Key words: Reciprocation; Particle; Suspension; Mixing time; Power number; Mixing efficiency.

1. INTRODUCTION

In the 1980s the operation utilizing oscillation or pulsation attracted attention in multi-phase fluid processing. Since then various fundamental and application studies have been conducted in column or tubular equipment. Orifice plates or ‘doughnut’ baffles are installed in the equipment, and oscillations are imposed to the fluid by pulsating a piston system or to the baffles plates by an oscillatory mechanism. The oscillation frequency is normally in the range of 0.5 to 6 Hz at the amplitude of 1 to 100 mm. The review by Ni et al. [1] is helpful for understanding the possibilities of this technique to unit operation dealing with multi-phase fluid processing in the chemical and process industries.

In the filed of mixing, oscillatory or time-periodic flows have attracted attention in relation to chaos since J.M. Ottino published a monograph on the kinematics of mixing, in which he demonstrated that certain unsteady flows can induce chaotic mixing [2]. However, little is known about chaotic behaviour of the flow induced by applying an oscillatory operation to a mechanically agitated vessel.

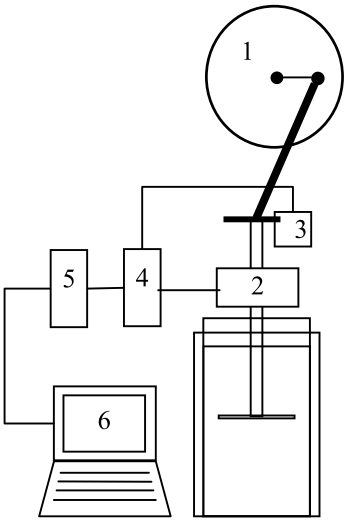
We have carried out a series of studies on flow and mixing characteristics in an agitated vessel with a disk impeller reciprocated up and down [3~6]. In our system the range of frequency is less than 1 Hz, being about one-sixth the frequency adopted in the oscillatory operations described above, but the amplitude is relatively large so that the motion of the reciprocating impeller covers, for example, two-thirds the liquid height [6]. The flow induced by disk reciprocation is divided into three types according to the Reynolds number: laminar creeping flow around the reciprocating disk at $Re < 20$, laminar flow with vortex generation at $20 < Re < 200$, and transient and turbulent flow with vortex generation at $Re > 200$. A ring vortex is generated behind the moving disk, which yields large elongation and folding of fluid interfaces that are essential to chaotic mixing [6]. In addition, the fluctuating velocities have the same order of the magnitude of reciprocating disk velocity [5]. In summary the flow induced in our recipro-mixing is gentle on the whole but fluctuates largely, in which fluid mixing is completed within a few reciprocations [6].

As described above, the recipro-mixing has various unique characteristics that the traditional rotational mixing may not possess. It will be therefore worthwhile to examine its potentials in the chemical and process industries, although its driving mechanism is not simple as compared to the rotating mixing and additional technical problems associated with reciprocation must be solved. As one of the potentials of this technique, we are interested in fluid mixing in suspensions since we expect that the particle motion, which may deviate from the fluid motion under the highly unsteady flow induced by disk reciprocation, may contribute to fluid mixing. In addition, the mild flow with large fluctuation induced at a low reciprocation frequency may find its needs in the operation dealing with suspensions of fragile materials such as cell culture, crystallization, etc. From this point of view, measurements of power and mixing time have been carried out in this study, based on which contributions of suspended particles to fluid mixing will be discussed.

2. EXPERIMENTAL

21 Experimental Apparatus

Experimental facilities are shown in Figure1. A circular disk is reciprocated in a cylindrical vessel through a cam mechanism connected to a flywheel rotated by a variable speed motor. The vessel and the disk were made of acrylic resin. The vessel was placed in a rectangular vessel of the same acrylic resin to reduce the optical distortion in observing the flow and mixing process. The vessel diameter, T, was 7.7cm and the liquid or suspension height, H, was 12cm. Two disks of 2mm in thickness were used as impellers, whose diameters, D, were 5.97cm ($D/T = 0.775$) and 6.89cm ($D/T = 0.894$). The opening ratio of the gap area between the disk edge and the vessel sidewall to the cross-sectional area of the vessel, $S = 1 - (D/T)^2$, was 0.4 for $D/T = 0.775$ or 0.2 for $D/T = 0.894$. The disk centrally located in the vessel was reciprocated with an amplitude $a = 4$ or 5 cm at a frequency N less than 1 Hz, and the reciprocation centre was set at 6 cm above from the bottom of the vessel.



1. fly wheel connected to a variable motor
2. force transducer 3. photo interrupter
4. strain amplifier 5. A/D converter 6. PC

Figure 1 Experimental facilities.

Experiments were carried out by using water or glycerol aqueous solutions, whose density was in the range of 997 ~ 1116 kg/m^3 and viscosity was in the range of 0.897 ~ 4.3 mPas. Two kinds of particles, polystyrene and ion-exchange resin, were used for preparing suspensions. The average diameter, d_p, and density, ρ_p, were 1.09, 0.65 or 0.54mm and 1060 kg/m^3 for polystyrene particles and 0.84mm and 1360 kg/m^3 for ion-exchange resin particles, respectively. The measurements were conducted under the condition where all the particles were fully suspended in liquids.

2.2 Measurement of Force Acting on the Disk Impeller

A load cell was used for measuring the force acting on the reciprocating disk. The details of its structure and the measuring method have been described in the papers [3,6].

2.3 Measurement of Mixing Time

The decolourisation reaction of iodine with sodium thiosulfate was used to measure mixing time. An iodine solution was filled up to the height of 12cm to prepare a suspension in the vessel and then disk reciprocation was started. A concentrated sodium thiosulfate solution of 2 cm^3, which contained a 25% excess of stoichiometric quantity required for decolourising the iodine solution, was poured calmly onto the liquid surface when the disk reached the highest position in reciprocation. Mixing time was measured as the time required for the whole liquid to become transparent.

3. RESULTS AND DISCUSSION

3.1 Reynolds Number

The following Reynolds number [3] is used for discussing the experimental results,

$$Re = \rho_{\mathrm{f}}(2\pi Na / S)(T - D) / \mu \qquad (1)$$

where the existence of solid particles has not been taken into account.

3.2 Force Acting on the Disk Impeller

Variations of the force acting on the disk during one cycle can be investigated by drawing a Lissajous figure in which the force is plotted against the disk position. Figure 2 shows the Lissajous figures obtained for D/T = 0.775, a = 4cm and N = 0.67 s^{-1} by suspending the polystyrene particles of d_{p} = 1.09 mm in water. The particle concentration was change from $\phi = 0$ to 0.45. The Reynolds number is 7180. In the figure, the force, f, and the disk position, z_{d}, have been converted into the following dimensionless quantities,

$$f^* = f / \{[\rho_f (2\pi Na / S)^2 / 2](\pi D^2 / 4)\} \qquad (2)$$

$$z_{\mathrm{d}}^* = z_{\mathrm{d}}/a \qquad (3)$$

The value of f^* is positive when the force direction is upward, and the highest and lowest positions of the disk are at $z_{\mathrm{d}}^* = 1$ and $z_{\mathrm{d}}^* = -1$, respectively. The force during one cycle changes in the counterclockwise direction on each Lissajous curve.

According to the previous study on flow characteristics [5], the flow at Re = 7180 is fully turbulent associated with the generation of a ring vortex behind the moving disk. The flow induced by disk reciprocation does not cease even when the disk reaches the turning position at $z_{\mathrm{d}}^* = 1$ or -1, exerting a force against the disk there. Hence the force is positive or upward at $z_{\mathrm{d}}^* = 1$ and negative or downward at $z_{\mathrm{d}}^* = -1$. While the disk is accelerating toward the reciprocation centre, the fluid in the front region of the moving disk is pushed away in the radial direction and the fluid near the disk edge is forced to flow through the gap between the disk edge and the vessel sidewall in the direction opposite to the disk movement. This compensating flow through the gap grows up while the disk increases its velocity, turning its direction toward the disk near the central axis in the rear region of the disk. Thus a circulating flow is formed around the moving disk and the fluid behind the disk rolls up to form a ring vortex. The force acting on the moving disk reaches a maximum while the circulating flow

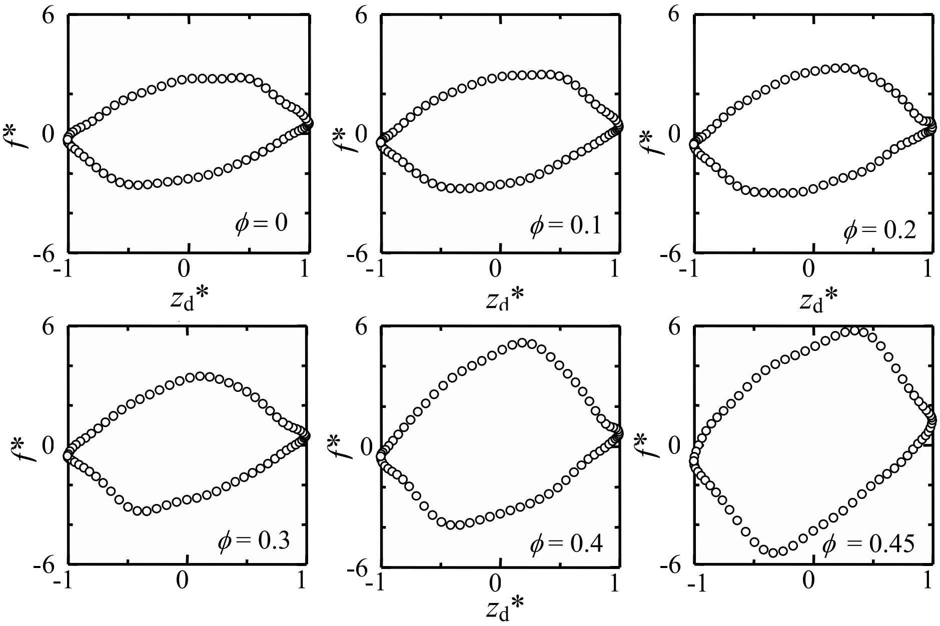


Figure 2 Lissajous curves of f^* and z_d^* obtained in the suspensions of polystyrene paritcles in water agitated at reciprocation frequency N=0.67 s^{-1}.

and the ring vortex are being formed. The disk velocity decreases past the reciprocation centre and the force decreases as the disk approaches the other end of reciprocation.

Lissajous curves of f^* and z_d^* in Figure 2 can be divided into two groups. At the low concentration of solid particles of $\phi < 0.2$ the curves are almost similar to each other. The dimensionless maximum force hardly changes in the range from $\phi = 0$ to 0.1 and increases a little at $\phi = 0.2$. With further increasing ϕ, the shape of Lissajous curve transforms into a more rectangular one and the maximum dimensionless forces at $\phi = 0.4$ and 0.45 are appreciably larger than those at the low concentrations.

Such differences in Lissajous curves are likely brought about by the difference in fluidity of suspensions. It is inferred that in the suspension at a low solid concentration of ϕ less than 0.2 the particles move relatively freely in the fluid with less collision with each other and the suspension behaves like a homogeneous fluid. On the other hand, the transformation of Lissajous curve into a rectangular one suggests that the flow in the dense suspension of ϕ larger than 0.3 is mainly governed by particle-impeller collision as well as particle-particle collision.

3.3 Power Number

The work of the disk impeller required for one reciprocation is given by the integration of the product of the force acting on the disk and the disk velocity over one reciprocation period. Then the power is obtained by dividing the work by the period, and the power number for recipro-mixing is defined as [3,6],

$$P_o = P / \{(\pi D^2/4)[\rho(2\pi Na/S)^2/2](2\pi Na)\} \tag{4}$$

Variations of the power number with Re are shown in Figure 3 for the suspensions of polystyrene particles. The power number for mixing liquids without particles has been correlated by $P_o = 44\ Re^{-1}$ at $Re < 20$ and $P_o = 1$ at $Re>200$ [6]. In mixing suspensions the power number varies similarly with Re, decreasing toward a constant value as Re increases. It

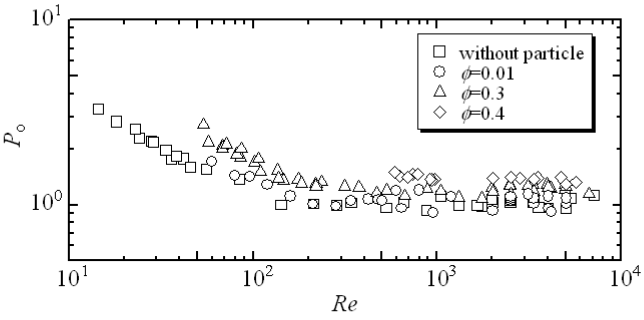


Figure 3 Variations of P_o with Re

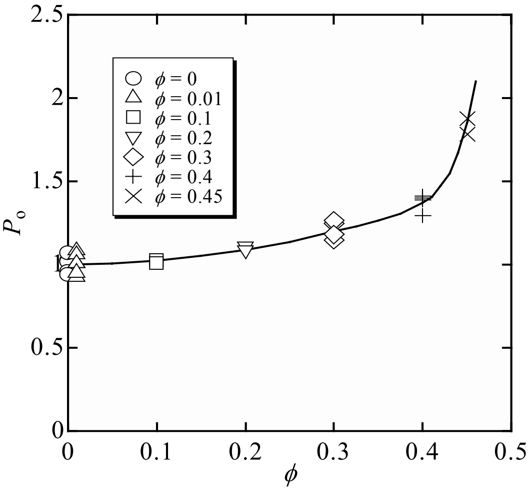


Figure 4 Dependency of constant P_o at large Re on ϕ

was hard to carry out the force measurement at Re less than 20 since it was very difficult to suspend lighter polystyrene particles in a glycerol solution with high viscosity.

The values of constant P_o obtained at $Re>10^3$ in the suspensions of polystyrene particles in water are plotted against ϕ in Figure 4. The power number is little affected by the suspended particles at $\phi < 0.2$, as shown in Lissajous curves of the dimensionless force variation. With further increasing ϕ, the power number increases appreciably.

In rotational mixing, the influence of particle concentration on the solid-liquid mixing characteristics has been investigated in detail by Nienow et al. [7], Takenaka et al. [8] and Takenaka et al. [9]. They identified five states of suspension by paying attention to the behaviour of the particles remaining on the bottom and the interface between the suspension and the liquid existing above it. With increasing stirrer speed, the power number also increases, passes through a maximum and eventually tends to be constant. At a stirrer speed larger than 600 rpm the power number increases from 0.31 for mixing only water up to 0.4 with increasing solid concentration [8]. It is hard to make a quantitative comparison of the influences of particle concentration on the power number in both mixing systems, because the flows are quite different from each other and the measurements in this study was restricted to the case where the particles were fully suspended.

3.4 Mixing Time

In measuring mixing time, the decolourizing reagent of sodium thiosulfate was poured calmly onto the liquid surface near the sidewall of the vessel when the disk impeller reached the highest position of reciprocation. This selection of feeding position and timing required longer time for completing mixing than the other selections. In the preliminary experiments carried out in the fully turbulent region at $Re > 10^3$, the maximum standard deviation of measured mixing time was 6% of the dimensionless mixing time $N\theta_M$.

To investigate the effects of density difference between particle and liquid on mixing time, the disk of d/D=0.775 was used for mixing polystyrene particles of 1.09 mm or ion exchange resin particles of 0.84 mm in water or a glycerol solution at $\phi = 0.01$. The dimensionless mixing time, $N\theta_M$, was plotted against the reciprocation frequency, N, in Figure 5. In the case without particles $N\theta_M$ is almo12st constant in the range of 2.4 to 2.5. A value of 2.5 means that fluid mixing is completed in two and a half reciprocations. $N\theta_M$ in suspensions is also independent of N, and a larger decrease in mixing time has been obtained for particles with a larger difference in density. $N\theta_M$ is about 1.6 for the density difference $\Delta\rho = 363$ kg/m^3, which is about 2/3 of $N\theta_M$ in mixing only liquids.

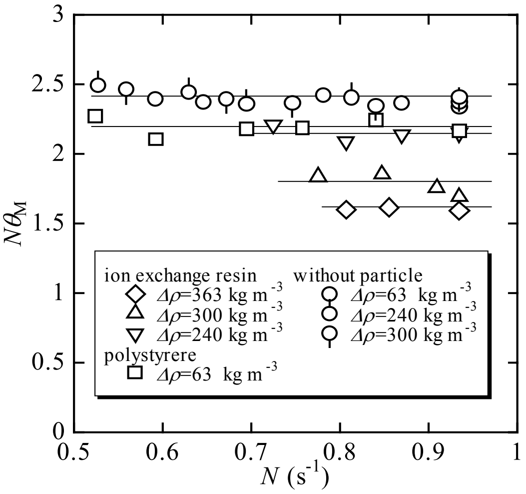


Figure 5 Variations of $N\theta_M$ with N for various density differences between particle and liquid

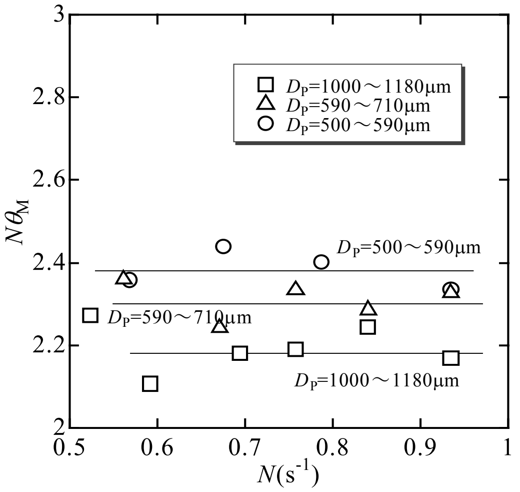


Figure 6 Variations of $N\theta_M$ with N for various sizes of polystyrene particles at ϕ=0.01

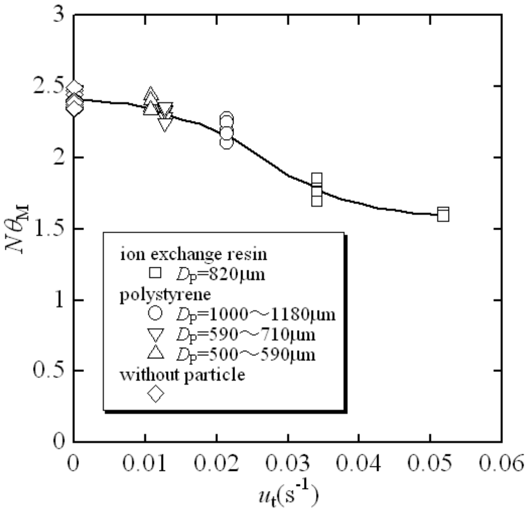


Figure 7 Variations of $N\theta_M$ with the gravitational settling velocity u_t of suspended particles

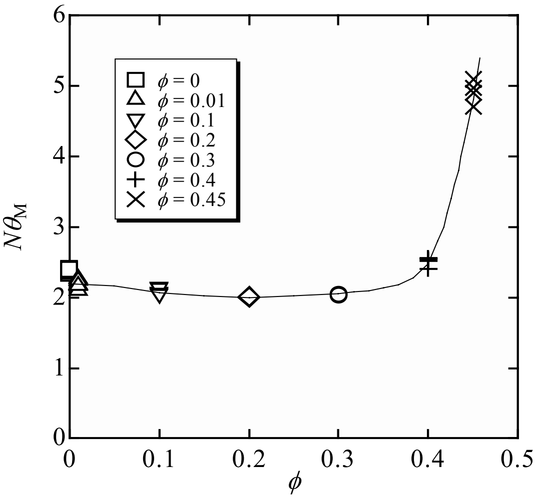


Figure 8 Variations of $N\theta_M$ with ϕ of polystyrene particles suspended in water

Figure 6 shows effects of particle size on $N\theta_M$ in the suspensions of polystyrene particles in water at $\phi = 0.01$. The density difference was kept at 63 kg/m^3 in this case. It is evident that larger particles are more effective for reducing mixing time.

Based on the visual observation with the naked eye, the suspension flow at $\phi = 0.01$ was highly turbulent due to the vortex generation behind the moving disk by every half reciprocation. Hence it is likely that particles with larger size and larger density difference have larger relative velocity in the unsteady fluid motion while settling down under the gravitational force. Variations of $N\theta_M$ shown in Figures 5 and 6 are well correlated with the settling velocity u_t, as shown in Figure 7, which demonstrates that the gravitational force is utilized for enhancing the rate of fluid mixing by the particle motion deviating from the fluid motion.

In Figure 8 effects of particle concentration on $N\theta_M$ are investigated by changing ϕ of polystyrene particles from 0.01 to 0.45 in water suspensions. $N\theta_M$ decreases with increasing ϕ at low particle concentrations, having a minimum in the range of $\phi = 0.2$ to 0.3 and turns to increase largely with further increasing ϕ. These variations of $N\theta_M$ with respect to ϕ may be reflected by the difference between particle and fluid motions in a suspension. At a low concentration of $\phi < 0.2$, the energy to generate the flow of suspension is mainly transferred from the impeller to the fluid. The fluid drives particle motion but the particles do not follow the fluid motion due to the finite particle size and the gravitational force caused by the possible density difference between the particle and the fluid. Hence, the particles moving about in the fluids may promote fluid mixing. At a high concentration of $\phi > 0.3$, on the other hand, the mixing energy is transferred mainly to particles by particle-impeller collision and particle-particle collision. The particles drive fluid motion and the fluid locally surrounded by densely suspended particles will follow the local particle motion. The force variations during one cycle in Figure 2 will support such reasoning. The fluid situation surrounded by particles may degrade fluid mixing in the dense suspension. It is interesting that the particle concentration of $\phi = 0.2 \sim 0.3$ is the boundary between enhancement and degradation in fluid mixing by the particles in a suspension.

In the rotational mixing of glassbeads in water by Lightnin A310 [7,8], with increasing the stirrer speed N, the dimensionless mixing time $N\theta_M$ increases from the constant value for water, having a maximum under the condition where a clear layer appeared in the upper part of the vessel. At the particle concentration of 40 w/wt%, the maximum was up to 50 times as large as $N\theta_M$ for mixing water alone. Further increase in stirrer speed caused $N\theta_M$ to decrease. At the highest speed at which the condition inside the vessel became more homogeneous, $N\theta_M$ did not show any appreciable dependency on the particle concentration, being close to $N\theta_M$ for water. The dependency of $N\theta_M$ on the particle concentration in recipro-mixing is quite different from that reported by them.

3.5 Energy Efficiency

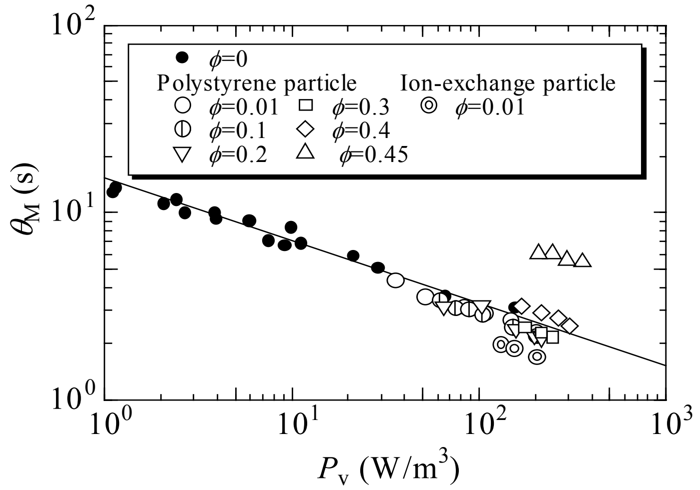


Figure 9 Comparison of energy efficiency in the plot of θ_M vs P_v.

The power required for fluid mixing in a suspension may be saved if the gravitational energy is utilized for this purpose. Figure 9 shows variations of mixing time θ_M with the power input per suspension volume, P_v. Mixing time in the ordinary rotating mixer varies in proportion to $P_v^{-1/3}$ in the turbulent region [10]. This relation also holds for recipro-mixing of miscible liquids in the turbulent region [6]. In Figure 9 the solid line with the tangent of $-1/3$ has been drawn to fit the data plotted by black circles, which were obtained for mixing liquids without particles at $Re > 10^3$ by using the impellers of $D/T = 0.775$ and 0.894. In the polystyrene suspensions, the data obtained at $\phi < 0.2$ are about 10% below the fitted line but those at $\phi = 0.4$ and 0.45 are above it. As for the ion-exchange resin particles with larger $\Delta\rho$, about one third reduction in θ_M was obtained under the same P_v. If a comparison is made for the same θ_M, the ratios of P_v in suspensions to P_v in liquids without particles are $(0.9)^3 = 0.73$ for the suspensions of polystyrene particles at $\phi < 0.2$ and $(2/3)^3 = 0.30$ for the suspensions of ion-exchange resin particles at ϕ=0.01, respectively.

These figures in P_V reduction demonstrate that the particles suspended in a dilute suspension at $\phi < 0.2$ contribute to saving mixing energy or to enhancing fluid mixing under a given power input..

4. CONCLUSION

Under the fully suspended condition in recipro-mixing, particle suspensions are classified into dilute suspensions and dense suspensions in terms of fluid mixing. In the suspension of polystyrene particles in water or glycerol solutions, the boundary between the dilute and dense suspensions was specified by $\phi = 0.2 \sim 0.3$ from the measurements of the force acting on the reciprocating disk impeller and those of fluid mixing in suspensions.

In a dilute suspension at ϕ less than 0.2, the Lissajous curve between the force and the disk position is smooth, being similar to that without particles and the power number is hardly affected by the existence of particles. Particles in the dilute suspension promote fluid mixing, and the effects of particle size and density on the dimensionless mixing time are correlated with the gravitational settling velocity for the suspensions at $\phi = 0.01$. In other words, the gravitational potential energy can be utilized for fluid mixing.

In a dense suspension at ϕ larger than 0.3, on the other hand, the Lissajous curve between the force and the disk position is like a rectangular one, and the power number and the time required for fluid mixing are much larger than those for mixing only liquids.

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